

**BELLCOMM, INC.**

955 L'ENFANT PLAZA NORTH, S.W.

WASHINGTON, D. C. 20024

B70 12058

SUBJECT: Preliminary Study of Steep LM  
Descent Trajectories Suitable  
for a One-Day Launch Delay  
Case 310

DATE: December 21, 1970

FROM: G. M. Cauwels  
J. A. Sorensen

ABSTRACT

LM descent trajectories which are designed with high elevation angles during the visibility phase to ease the washout problem of a T + 24 launch are analyzed. The design of these trajectories is briefly discussed, and the sensitivities of the trajectory cost to variations of the minimum visibility phase elevation angle and high gate altitude are investigated. An example trajectory with a minimum elevation angle of  $28^\circ$  is found to cost 70 ft/sec more  $\Delta V$  (characteristic velocity) for automatic landing than that of the Apollo 12 trajectory. The steep trajectory nominally has only 6 sec less visibility time than the Apollo 12 trajectory, but it has a significantly increased cost of landing point redesignations. Other trajectory comparisons are made and sensitivities to trajectory constraints are computed.

(NASA-CR-116237) PRELIMINARY STUDY OF STEEP  
LM DESCENT TRAJECTORIES SUITABLE FOR A  
ONE-DAY LAUNCH DELAY (Bellcomm, Inc.) 22 p

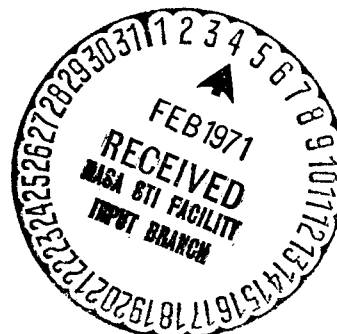
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MEMORANDUM FOR FILEI. INTRODUCTION

The option exists in mission planning to launch one day late, a so called T + 24 launch. Since it is often costly to decrease translunar flight time, the sun elevation angle can increase the normal  $12^\circ/\text{day}$ , and be in the range of  $20^\circ - 26^\circ$ . Present descent trajectories have a  $16^\circ$  elevation angle during the visibility phase, which means that shadows cast by the sun will not be visible down sun (only off to the side, and then usefully only for angles greater than  $20^\circ - 30^\circ$ ). Because of the peculiar reflective properties of the moon's surface (light tends to be reflected back to the source), this sun-trajectory relationship causes the so called "washout problem"; the crew has difficulty distinguishing boulders and craters that lie ahead.

Using a trajectory elevation angle\* of greater than  $26^\circ$  will make shadows again visible, which can be a major advantage of steeper trajectories. They also ease targeting to rougher lunar landing sites by increasing terrain clearance, and enable the flight crew to have a closer first look at the landing site following pitch-over at high gate (7000 ft altitude). These latter features are of interest even with the sun angles for a T + 0 launch.

In this study, a minimum allowable elevation angle of  $28^\circ$  was assumed in order to provide a  $2^\circ$  sunline-trajectory clearance for a T + 24 launch, to a site having a nominal sun elevation of  $14^\circ$ . The trajectories were designed so that most of the normal descent constraints were met, and the  $\Delta V$

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\*The elevation angle is defined as the angle between the line-of-sight from the LM to the landing site and the horizontal plane passing through the landing site.

(characteristic velocity required to automatically reach the landing site) was minimized. The design procedure is briefly outlined in the appendix.

In the following discussion, the  $\Delta V$  and look time (amount of time the landing site appears in the LM window) sensitivities to variations in high gate elevation angle, high gate altitude, and the 500 ft altitude rate-of-descent constraint are analyzed. The effect of allowing the trajectory to droop during the visibility phase is also investigated. Finally, the characteristics of the  $\Delta V$  optimal  $28^\circ$  trajectory are compared with the nominal Apollo 12 descent trajectory.

## II. SENSITIVITY OF TRAJECTORIES TO CONSTRAINT VARIATIONS

One set of trajectories studied was constrained to have constant glide slopes of  $28^\circ$ ,  $30^\circ$ , and  $32^\circ$  during the visibility phase. Also studied were trajectories with high gate elevation angles of  $30^\circ$  and  $32^\circ$  which were allowed to droop to the minimum elevation angle of  $28^\circ$ . High gate altitudes were fixed at 7000, 8000, and 9000 ft. The magnitude of the vertical rate at 500 ft altitude was constrained to be 16 ft/sec.

The visibility phase  $\Delta V$  cost of these trajectories is shown in Fig. 1. Here, no effort was made to fix the amount of time the LPD look angle (the angle between the nominal landing site and the forward body axis of the LM) is greater than  $-55^\circ$ .<sup>\*</sup> For this phase of the trajectory, lowering the high gate altitude lowers  $\Delta V$  because less distance is traveled to landing and consequently, less burn time is elapsed. Decreasing the elevation angle from a fixed high gate altitude increases the LM's distance away from the landing site and therefore increases  $\Delta V$  for the visibility phase.

Allowing the trajectory to droop saves  $\Delta V$  during the visibility phase because it moves high gate closer to the landing site for a given minimum elevation angle. It also provides the additional advantage of increasing the amount of time the look angle is greater than  $-55^\circ$ . This look time is presented in Table 1.

It can be shown that varying the minimum elevation angle allows partial control of the look angle time

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<sup>\*</sup>The bottom of the LM window is about  $65^\circ$  below the forward body axis of the LM. The LPD look angle is useful if it is more than  $10^\circ$  above the window bottom.

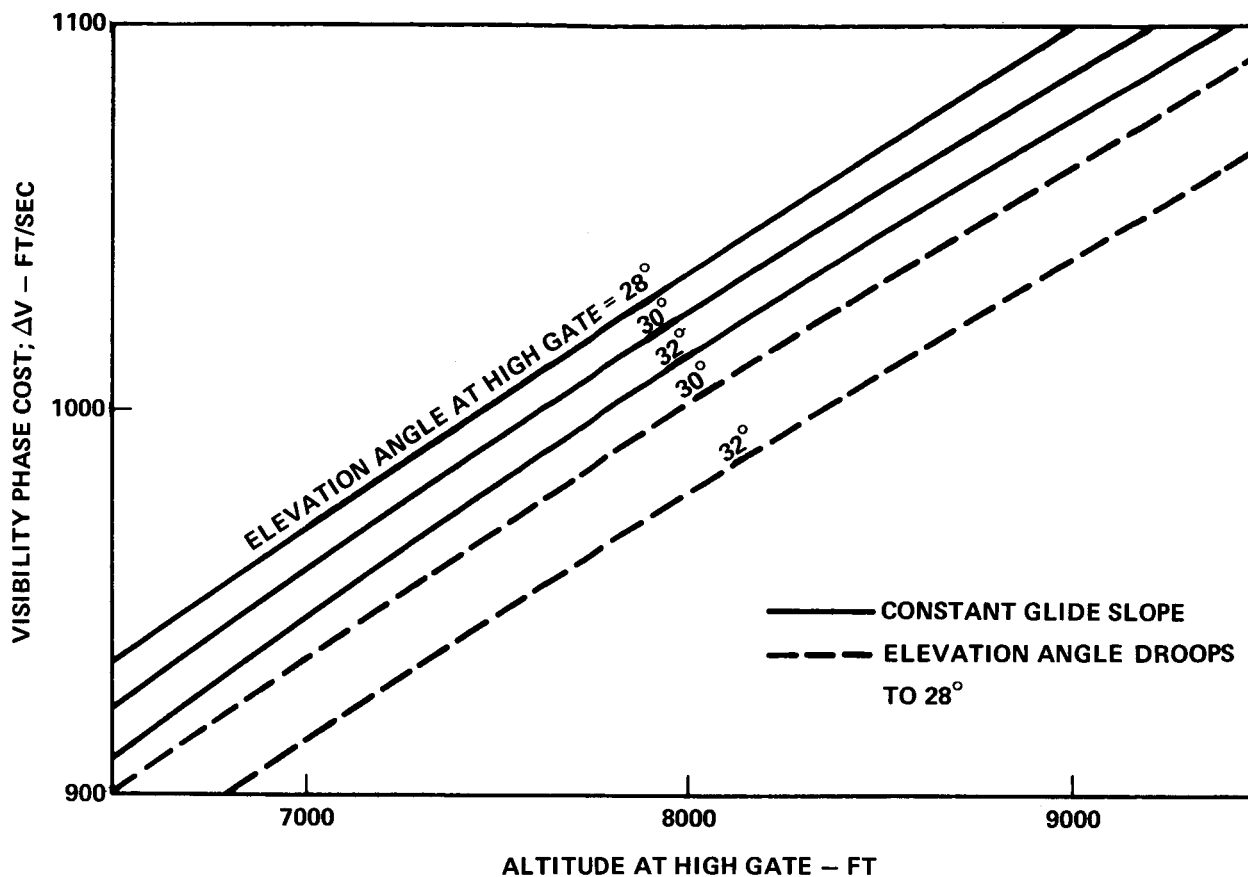


FIGURE 1 - ΔV COST OF STEEP VISIBILITY PHASE TRAJECTORIES

Table 1. Visibility Phase Time Where Look Angle is Greater Than -55°

High Gate Altitude, ft	High Gate Elevation Angle deg	Constant Elevation Angle Case, sec	Drooping Elevation Angle Case sec
7000	28"	108	
"	30	104	114
"	32	100	120
8000	28°	116	
"	30	112	118
"	32	104	126
9000	28°	122	
"	30	116	126
"	32	110	132

history. Increasing the droop by decreasing the minimum elevation angle moves the initial view of the landing site higher in the LM window. (A constant look angle can ease the problem of locating and evaluating the landing site.) However, because the emphasis here was to minimize  $\Delta V$  while meeting the minimum elevation angle constraint of  $28^\circ$ , no attempt was made to control the time rate of change of the look angle.

The variations which affect the  $\Delta V$  cost during the visibility phase have the opposite effect during the braking phase. The braking phase  $\Delta V$  is decreased by increasing the high gate altitude and by using a high gate velocity corresponding to a low, constant glide slope during the visibility phase. The braking phase cost sensitivity is shown in Fig. 2.

To find the minimum overall  $\Delta V$  trajectory having a minimum elevation angle constraint of  $28^\circ$  during the visibility phase, the costs in Figs. 1 and 2 are added. The resulting overall cost is presented in Fig. 3. It can be seen that the trajectory having the lowest  $\Delta V$  cost is one with the lowest high gate altitude and a small amount of droop.

Variations of the constraints used to target the steep trajectory can also affect the  $\Delta V$  cost of such a trajectory. Changing the vertical rate constraint at 500 ft altitude from -16 ft/sec to -18 ft/sec caused a  $\Delta V$  savings of 45 ft/sec during the visibility phase. This was accompanied by a 10 sec decrease in look time above  $-55^\circ$ . Increasing the vertical rate during the landing phase would also decrease the  $\Delta V$  cost.

### III. CHARACTERISTICS OF THE STEEP TRAJECTORY

To evaluate the characteristics of the steep approach, a trajectory with a  $30^\circ$  elevation angle at a 7000 ft high gate altitude which droops to  $28^\circ$  is used here as a typical example. This trajectory is now compared with the nominal Apollo 12 descent. Table 2 presents the trajectory states at high gate, low gate, 500 ft altitude, and 2000 ft horizontal range. The Apollo 12 trajectory, which starts at high gate with an elevation angle of  $16^\circ$  and droops to  $13^\circ$ , costs about 70 ft/sec less  $\Delta V$  (equivalent to 120 lb propellant or 13 sec of hover time) for an automatic landing. The steep trajectory's horizontal rate at 2000 ft range is reduced by about 26 ft/sec.

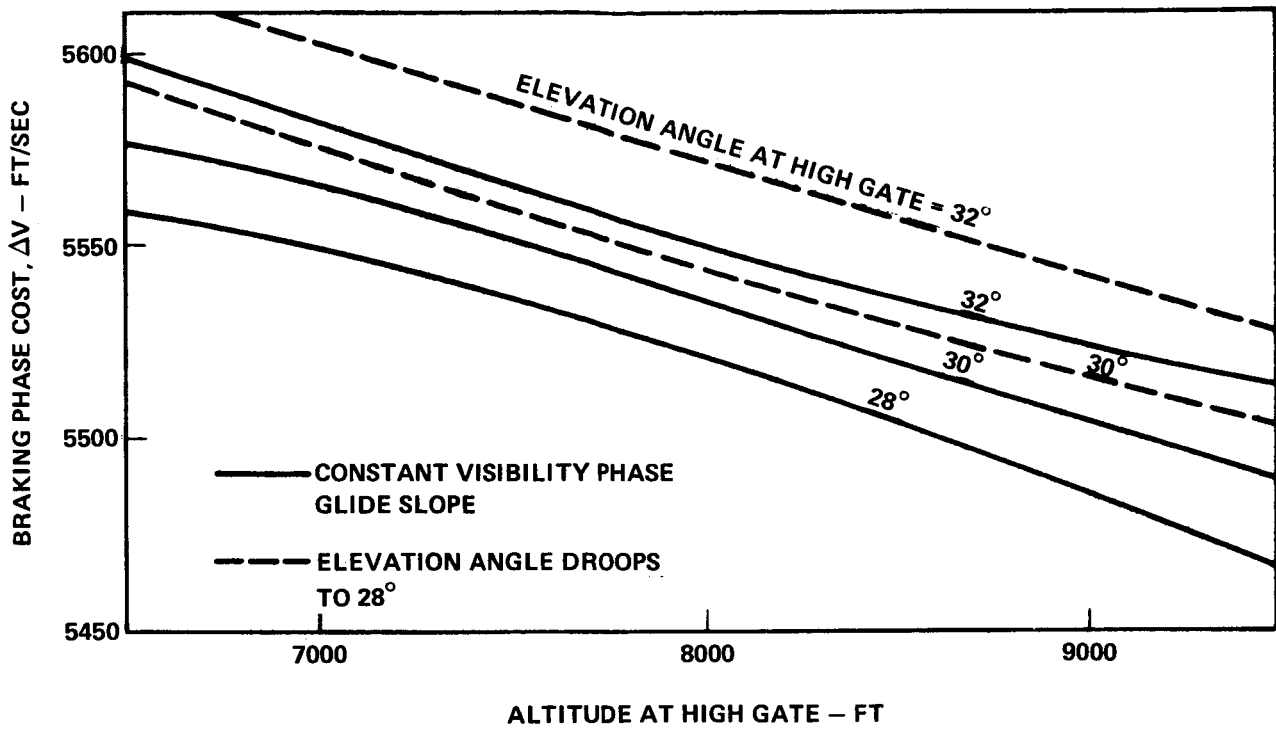


FIGURE 2 -  $\Delta V$  COST OF BRAKING PHASE ASSOCIATED WITH VISIBILITY PHASE TRAJECTORIES OF FIGURE 1

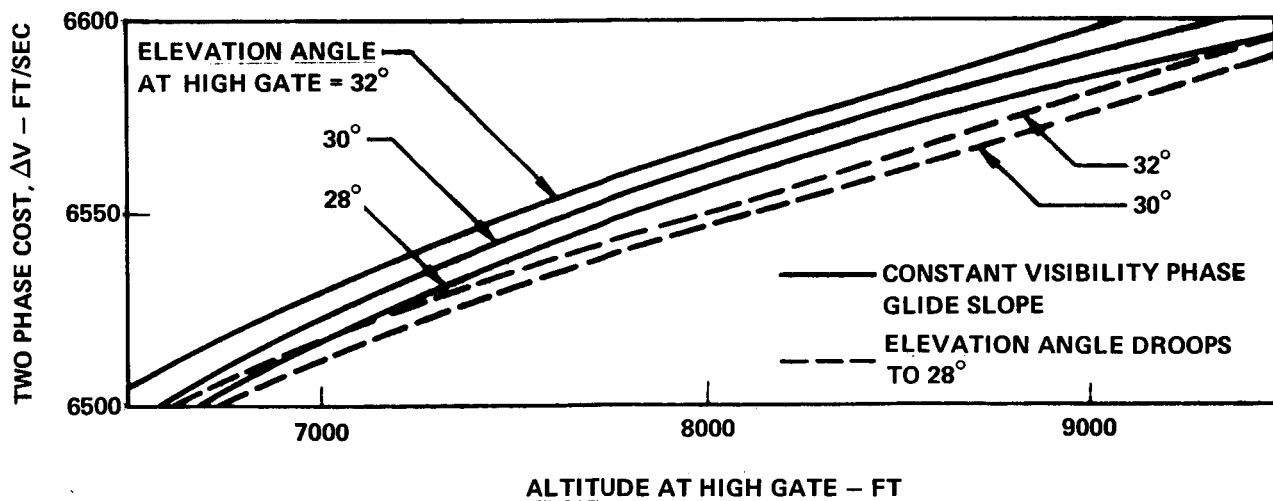


FIGURE 3 -  $\Delta V$  COST OF BRAKING PHASE AND VISIBILITY PHASE FOR STEEP GLIDE SLOPE TRAJECTORIES

Table 2. Comparison of 28° Trajectory and the Apollo 12 Trajectory

	<u>28° Trajectory</u>	<u>Apollo 12 Trajectory</u>
State at high gate		
Vertical position, x-ft	7000.	6999.
Horizontal position, z-ft	-12125.	-24411.
Vertical rate, x-fps	-173.8	-168.
Horizontal rate, Z-fps	268.6	447.0
Time past ignition-sec	510.	500.
$\Delta V$ -fps	5578.	5400.
State at 2000 ft range		
Vertical position, X-ft	1096.	552.
Vertical rate, X-fps	-29.4	-17.0
Horizontal rate, Z-fps	60.9	86.6
Time past ignition-sec	582.	593.
$t_{go}$ -sec	75.0	59.3
$\Delta V$ -fps	6141.	6135.
State at 500 ft altitude		
Horizontal position, Z-ft	-763.	-1735.
Vertical rate, X-fps	-15.8	-15.8
Horizontal rate, Z-fps	31.6	78.8
Time past ignition-sec	609.	597.
$\Delta V$ -fps	6303.	6155.
State at low gate		
Vertical position, X-ft	104.	98.
Horizontal position, Z-ft	-54.	-46.
Vertical rate, X-fps	-4.6	-2.8
Horizontal rate, Z-fps	6.8	5.6
Time past ignition-sec	645.	642.
$\Delta V$ -fps	6517.	6430.
Automatic landing conditions		
Time past ignition	675.	674.
$\Delta V$ -fps	6669.	6598.
Propellant used-lb	16584.	16462.
Radar on for smooth lurain		
Altitude-beam on altitude-ft	41632.	39692.
Velocity-beam on altitude-ft	28524.	26516.*
Minimum glide slope-deg	28°	13°

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\*Velocity-beam off at 2343. ft.

The  $\Delta V$  cost of the two trajectories can be compared in several other ways. At the 500 ft altitude point, the Apollo 12 trajectory costs 194 ft/sec less  $\Delta V$ . At the 2000 ft range point, the Apollo 12 trajectory costs only 6 ft/sec less.

A comparison was made of the  $\Delta V$  costs for LPD redesignation of these two trajectories. The landing site was redesignated with a single command at 4000 ft altitude. The results are presented in Figure 4 which shows the change in  $\Delta V$  and maximum bank angle as parameters. As can be seen, the  $28^\circ$  trajectory costs about 3 times as much for the same downrange-crossrange redesignation.

To redesignate short, the LM must be pitched back to cancel the vehicle's forward speed more rapidly. Decreased range increases the change in the flight path angle required to produce the short redesignation. Consequently, the vehicle pitch up must be greater for a steep trajectory; this more readily causes the landing site to drop visually out the bottom of the LM window.

The nominal look angle time histories of the  $28^\circ$  trajectory and the Apollo 12 trajectory are compared in Fig. 5. The steep trajectory has nearly the same (6 sec less) look time above the window bottom and 22 sec less time (114 sec vs. 136 sec) above the  $55^\circ$  line. Again, it is noted that the  $28^\circ$  trajectory was designed so that  $\Delta V$  was minimized, and therefore, its look angle has a faster time rate of change. To make the look angle more constant for the first part of the visibility phase and to meet the minimum elevation angle constraint of  $28^\circ$  would require shortening the high gate range at a cost of increased  $\Delta V$ .

Figures 6-12 show other comparisons of the  $28^\circ$  trajectory with the Apollo 12 reference trajectory. Figures 6 and 7 show the trajectory altitudes as a function of time past ignition and range from the landing site. In both, the effect of the steeper visibility phase is shown to cause the trajectory to remain longer at higher altitudes during the braking phase. Figures 8a and 8b compare the trajectory altitudes during the visibility phase. Note that in Fig. 8b the ratio of altitude to range during the final portion of the  $28^\circ$  visibility phase is about twice that of Apollo 12. Figure 9 compares the vertical rates of descent as a function of time past ignition. The steeper trajectory has a higher



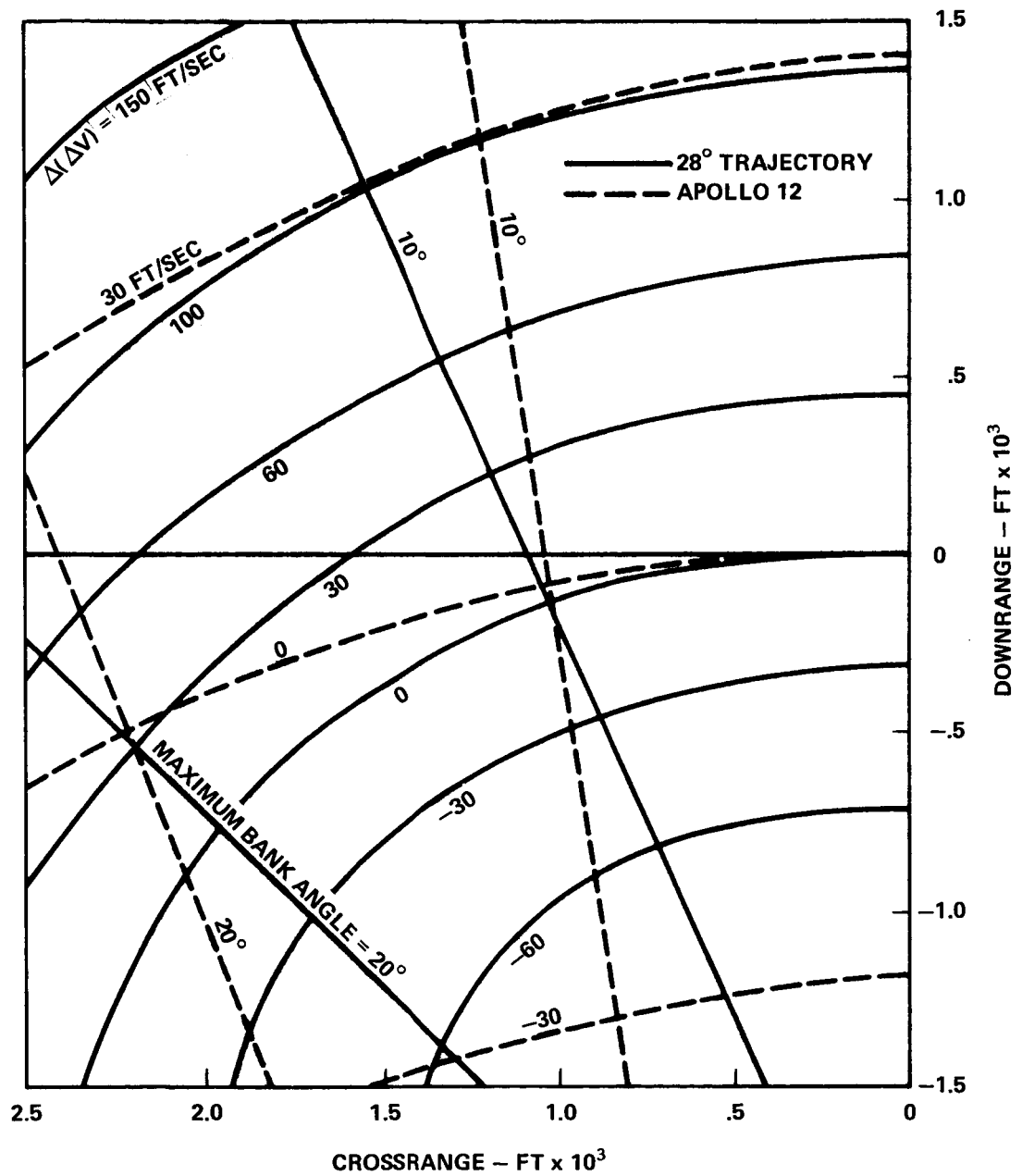


FIGURE 4 - COMPARISON OF LPD REDESIGNATION  $\Delta V$  COST FROM 4000 FT ALTITUDE FOR THE 28° TRAJECTORY AND THE APOLLO 12 TRAJECTORY. ALSO SHOWN AS A PARAMETER IS THE MAXIMUM BANK ANGLE REACHED WHILE ACHIEVING THE REDESIGNATION.

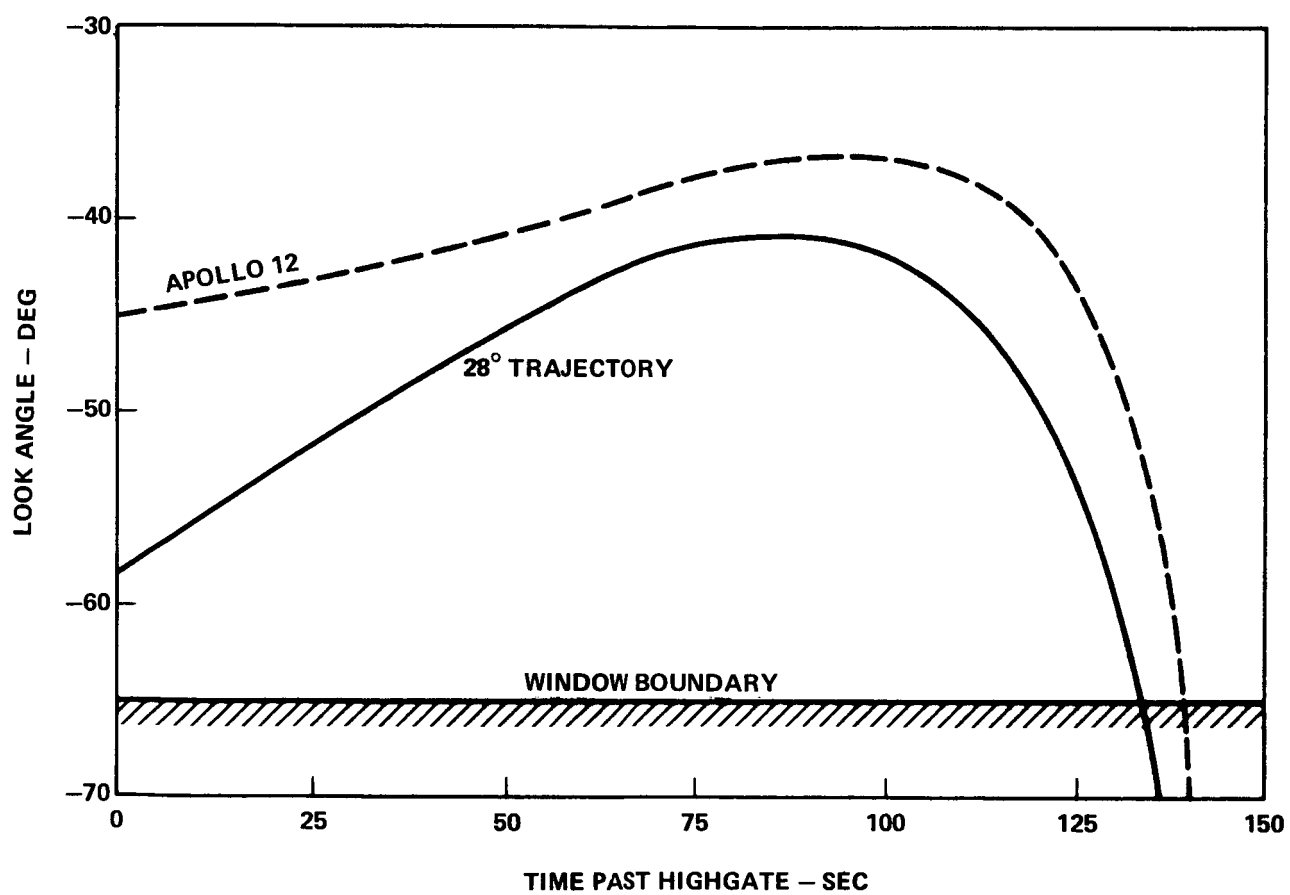


FIGURE 5 - COMPARISON OF LPD LOOK ANGLES FOR THE NOMINAL APOLLO 12 TRAJECTORY AND THE OPTIMUM 28° TRAJECTORY.

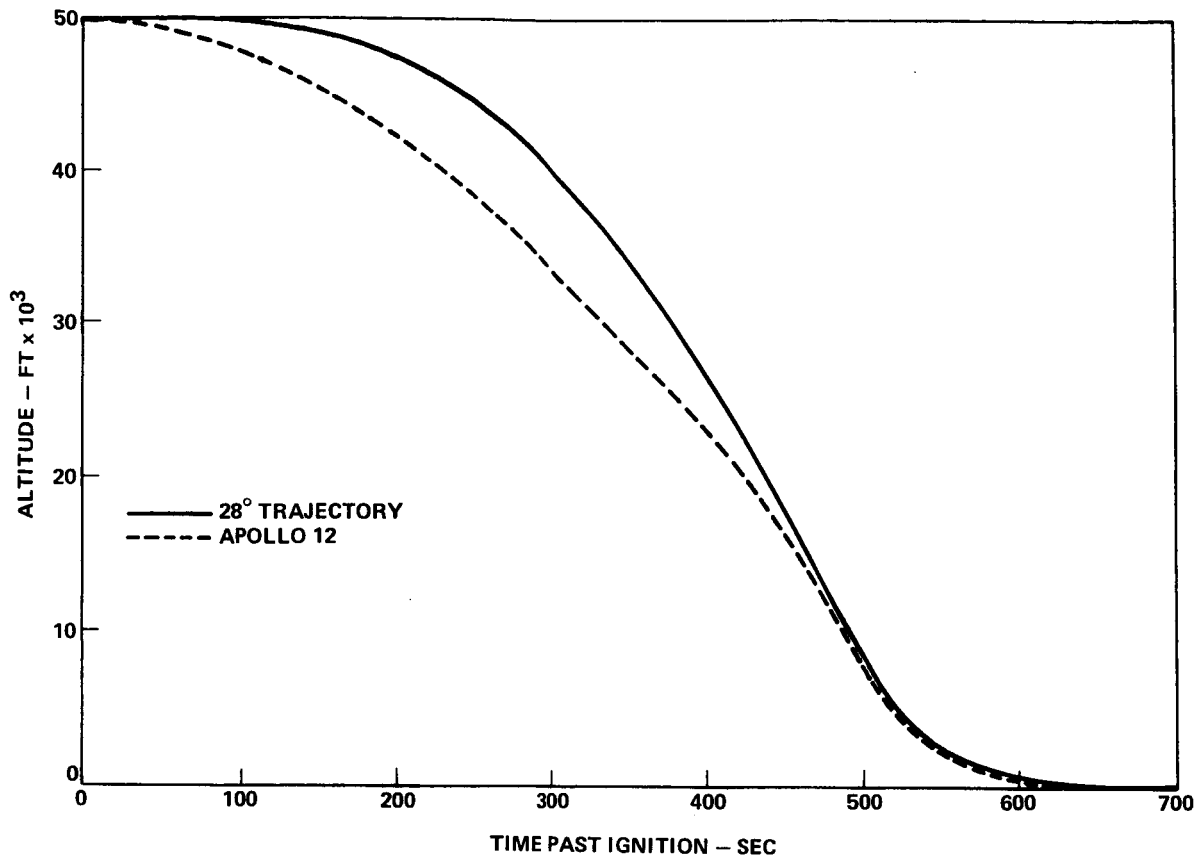


FIGURE 6 - TRAJECTORY ALTITUDE AS A FUNCTION OF TIME PAST IGNITION

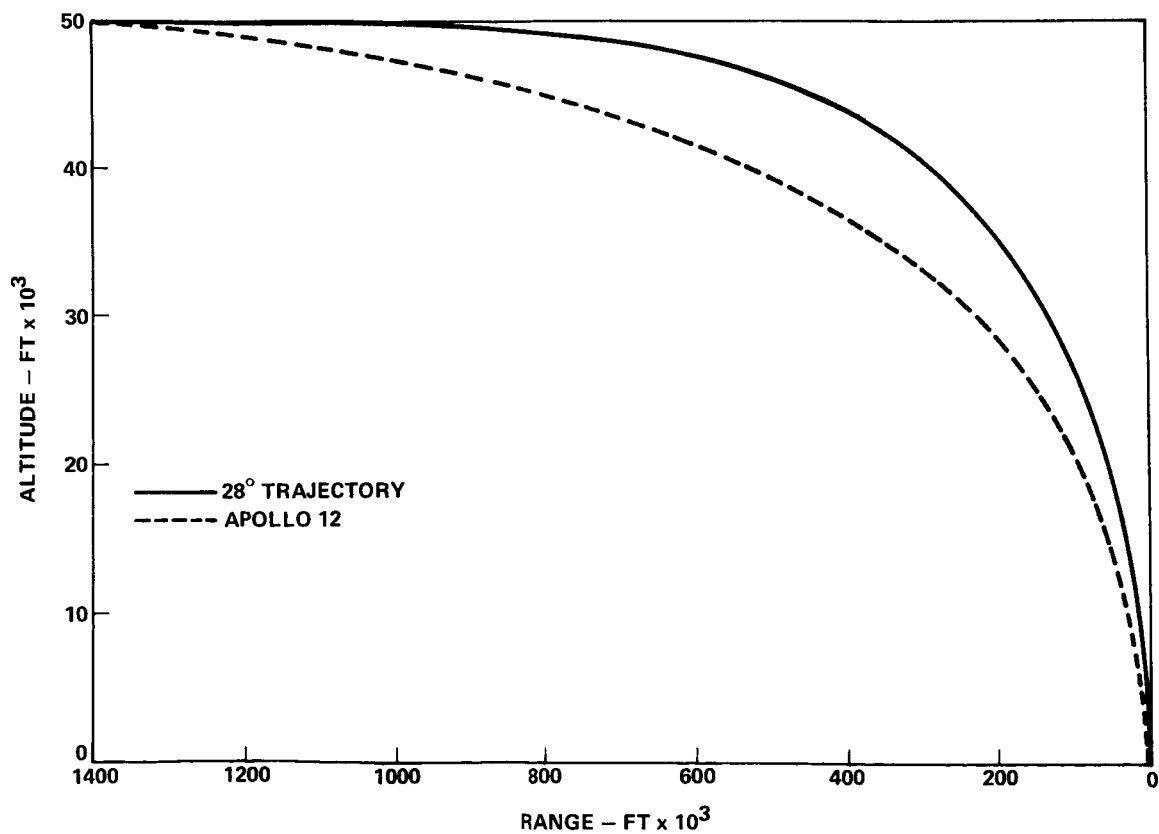


FIGURE 7 - TRAJECTORY ALTITUDE AS A FUNCTION OF RANGE FROM THE LANDING SITE

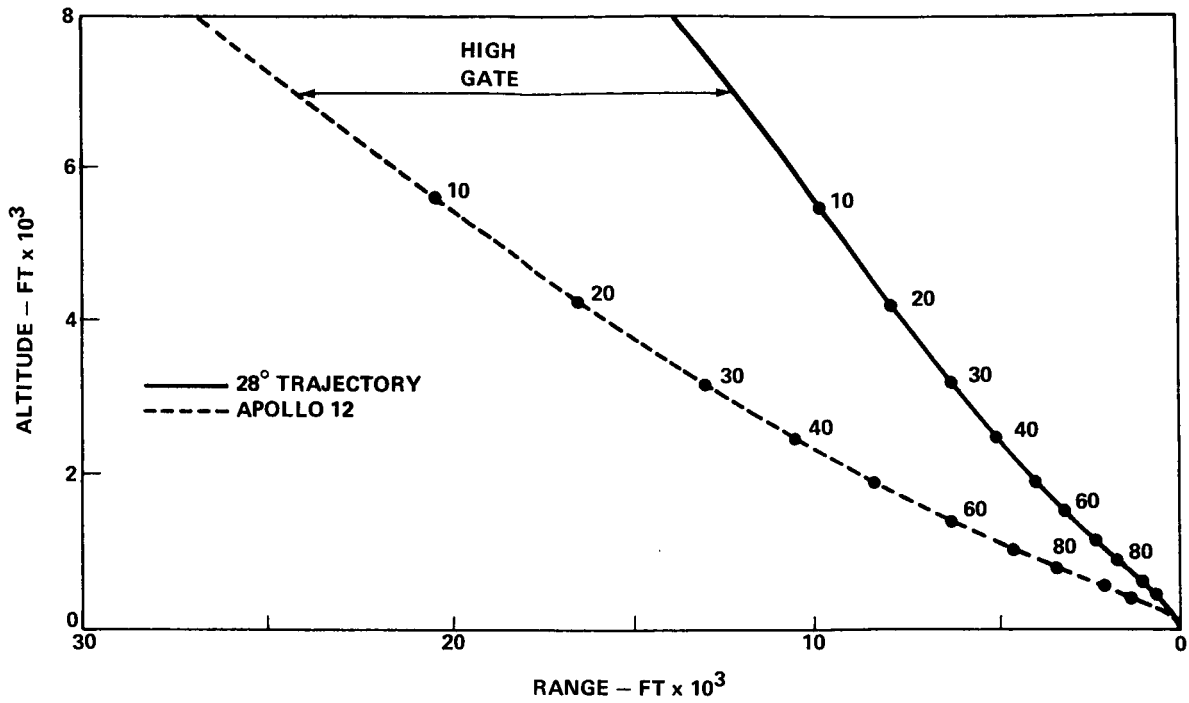


FIGURE 8a - TRAJECTORY ALTITUDE AS A FUNCTION OF RANGE FROM THE LANDING SITE DURING THE VISIBILITY PHASE. NUMBERS INDICATE TIME IN SECONDS PAST HIGH GATE

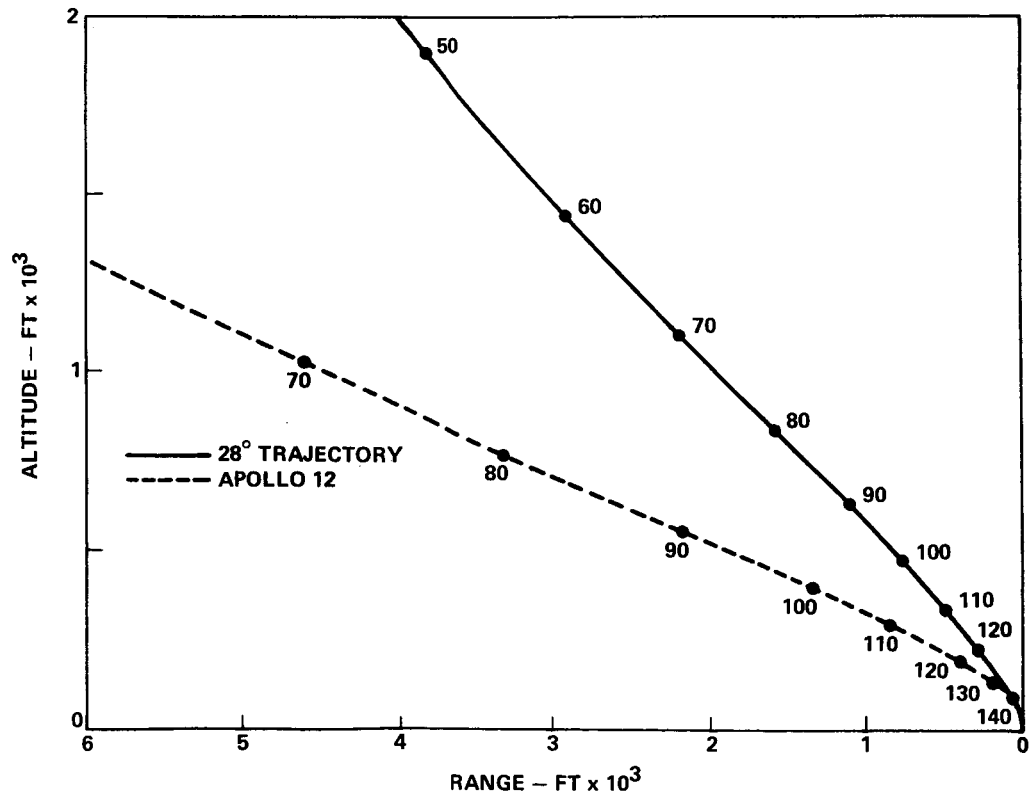


FIGURE 8b - CLOSER VIEW OF ALTITUDE VS RANGE DURING THE VISIBILITY PHASE. TIME PAST HIGH GATE IS INDICATED

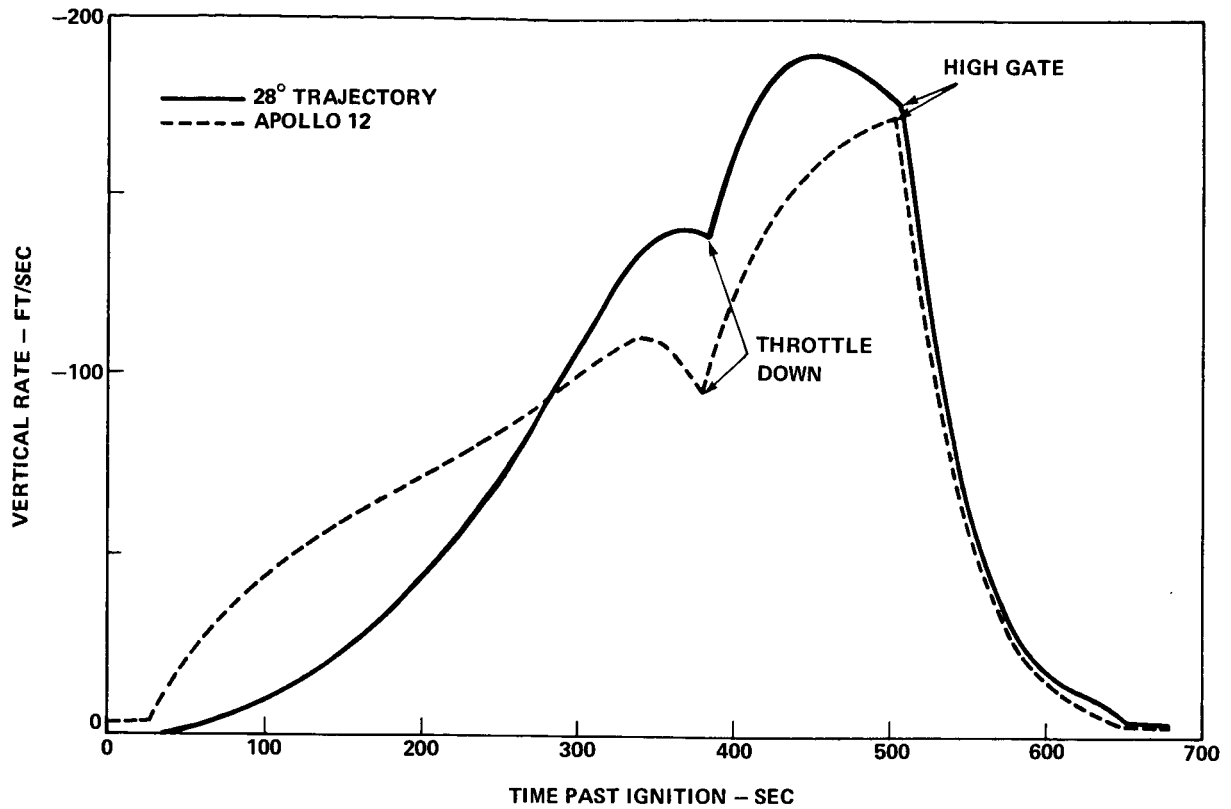


FIGURE 9 - VERTICAL RATE AS A FUNCTION OF TIME PAST IGNITION

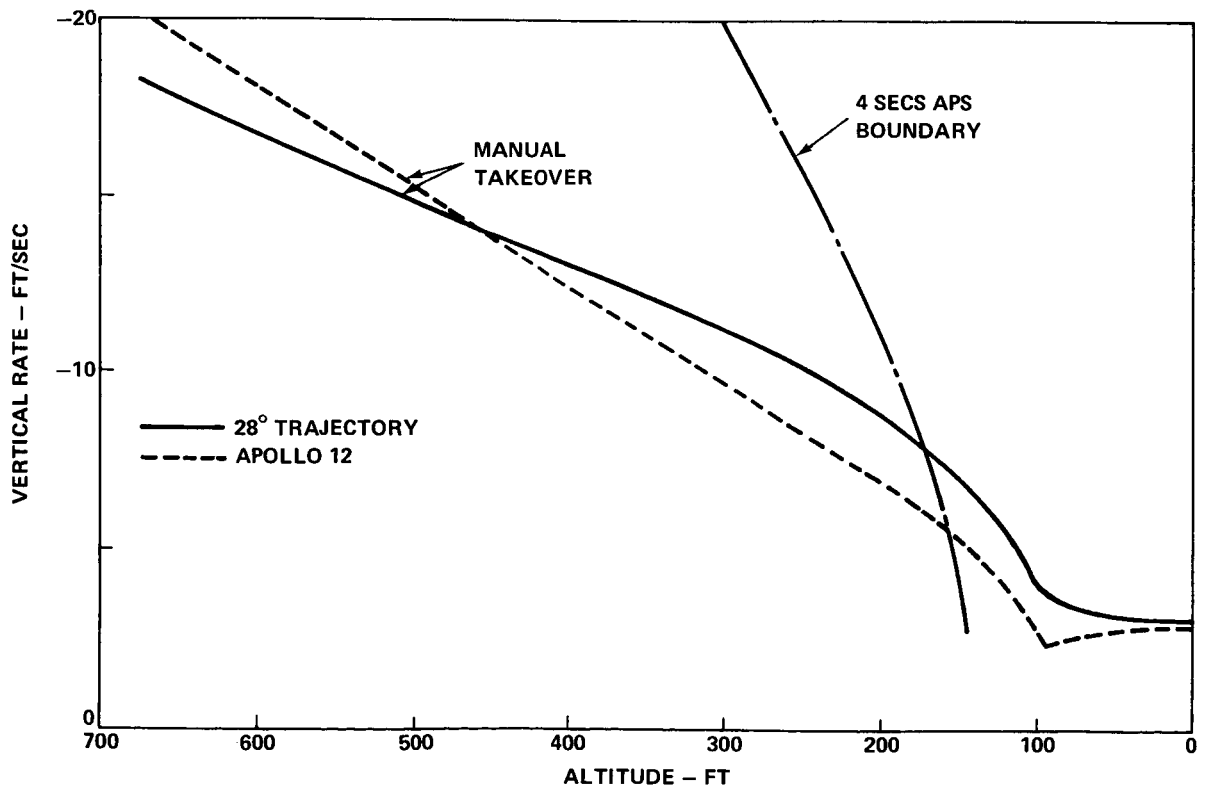


FIGURE 10 - VERTICAL RATE AS A FUNCTION OF ALTITUDE DURING THE FINAL PORTION OF FLIGHT. THE NOMINAL MANUAL TAKEOVER POINT AND THE APS ABORT BOUNDARY ARE ALSO SHOWN

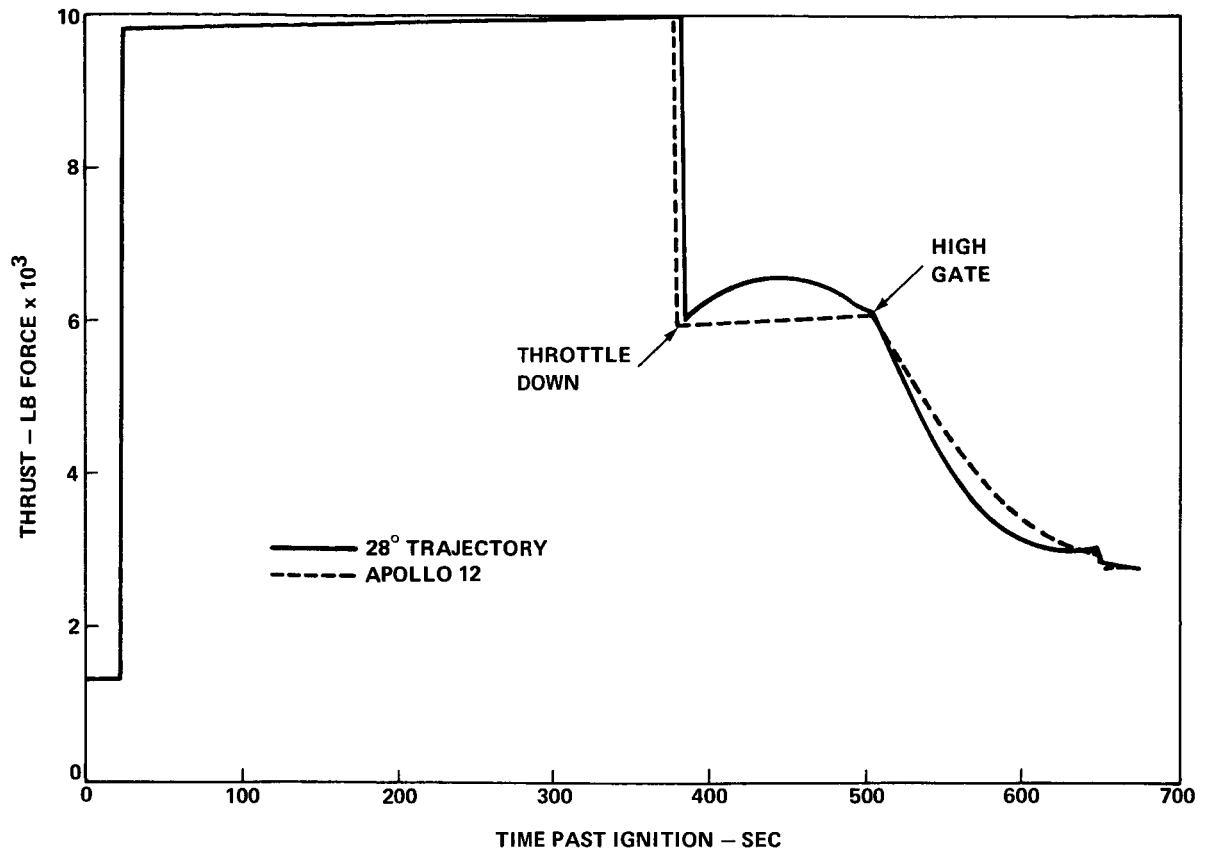


FIGURE 11 - ENGINE THRUST AS A FUNCTION OF TIME

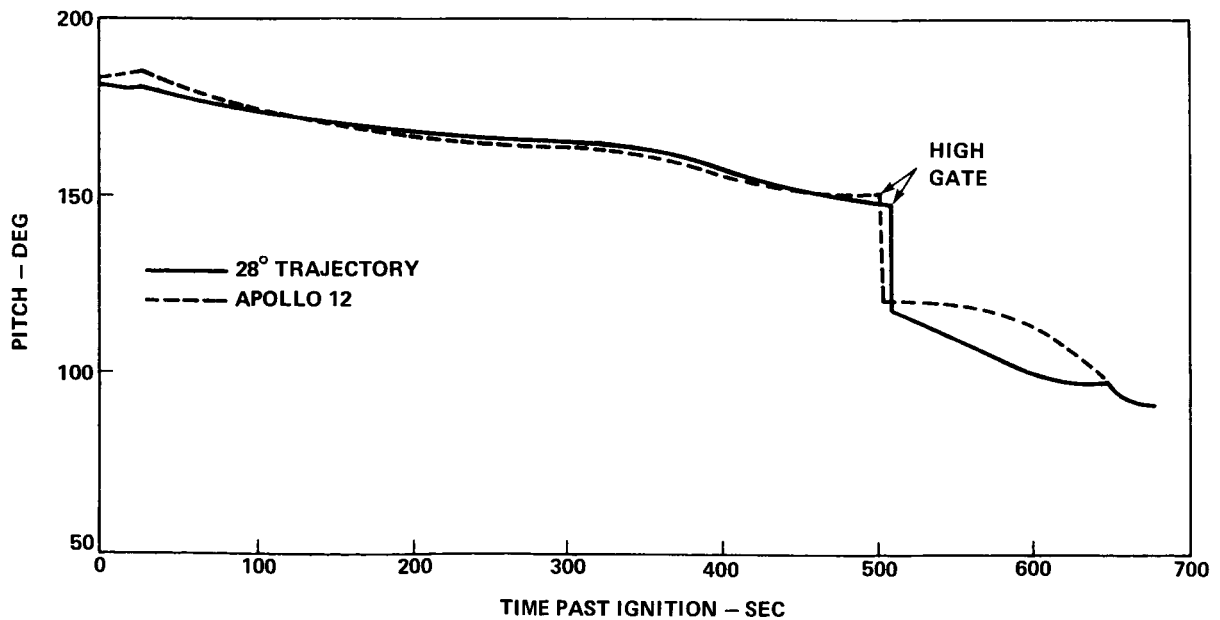


FIGURE 12 - VEHICLE PITCH ANGLE AS A FUNCTION OF TIME, 90° IS THE VERTICAL POSITION

peak rate which occurs before high gate. The rate during the visibility phase is essentially the same as that of Apollo 12. Figure 10 illustrates the vertical rates as functions of altitude near the end of the visibility phase. The  $28^\circ$  trajectory crosses the APS 4 sec abort boundary curve well after the 200 ft altitude mark. Figure 11 compares the thrust profiles of the two trajectories. They are similar except during the throttle-down portion of the braking phase when the steeper trajectory has a hump in its profile. This hump can cause throttle-up to occur when flying over rougher terrain, but it can be flattened by retargeting with a small cost in  $\Delta V$ . Figure 12 depicts the pitch angles of the vehicles during descent with the only marked difference occurring during the visibility phase of flight.


#### IV. CONCLUSIONS

From this preliminary study, the following observations can be stated about a trajectory suitable for a one day launch delay:

1. A trajectory designed to have an increased minimum elevation angle above the landing site during the visibility phase has an increased  $\Delta V$  cost to land automatically. A trajectory having a minimum elevation angle of  $28^\circ$  was found to cost 70 ft/sec more to land automatically than the Apollo 12 trajectory with other constraints being the same.
2. To minimize the overall  $\Delta V$  of the steep trajectory, high gate should be at the lowest acceptable altitude. Also, the visibility phase of the trajectory should have a small amount of droop.
3. Changing the vertical rate constraint of 16 ft/sec to 18 ft/sec at 500 ft altitude results in a  $28^\circ$  trajectory costing only about 25 ft/sec more  $\Delta V$  for automatic landing than the Apollo 12 trajectory.
4. Downrange-crossrange redesignations on the  $28^\circ$  trajectory cost about 3 times as much as those of the Apollo 12 trajectory. Short redesignations (uprange) cause the landing site to drop visually out of the LM window more readily for the steeper trajectory.

5. The total time the flight crew nominally has to look at the landing site is slightly reduced for the steep trajectory (134 sec vs. 140 sec).
6. The 28° trajectory and the Apollo 12 trajectory have essentially the same vertical speed profiles during the visibility phase. The 28° trajectory's horizontal speed is reduced.

It is concluded that, although there are penalties in  $\Delta V$  cost and look time, a trajectory designed with a steep approach during the visibility phase provides a possible solution to the visibility washout problem of a T + 24 launch.

  
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2014-GMC-ksc  
JAS

Attachment  
Appendix



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REFERENCES

1. Moore, T. E., "LM Descent Targeting and Final Approach Constraints," NASA MSC Memorandum EG27-254-68, September 6, 1968.
2. Moore, T. E., "LM Powered Descent Trajectory Constraints," NASA MSC Memorandum EG27-68-268, October 11, 1968.

APPENDIX

Targeting Procedure for High Elevation Angle Trajectories

The targeting (trajectory shaping) technique followed is to find an overall trajectory which meets the constraints and minimizes the  $\Delta V$  required to land. The required high gate position and velocity are unknown. Therefore, a dynamic programming procedure is followed in which the visibility phase is first optimally targeted starting from several assumed high gate states. The braking phase is then targeted to each of these states. The overall optimal trajectory is obtained from the best combined two phases. Targeting of each phase is now discussed.

A. Visibility Phase

The documented constraints of the visibility phase are from References 1 and 2. Those most pertinent to trajectory shaping during this phase are:

1. The landing site must visually be above a line in the LM window which is  $55^\circ$  below the forward axis of the LM for  $t_{go}$  (time-to-go to aim point)  $\leq 75$  sec until  $R_{go}$  (range-to-go to final target) is  $< 250$  ft.
2.  $t_{go} \geq 55$  sec at  $R_{go} = 2000$  ft.
3. The glide slope angle is  $\leq 20^\circ$  from  $t_{go} \leq 75$  sec until loss of visibility.
4. The altitude above which a safe abort can be made using the ascent propulsion system (APS) and assuming a 4 sec delay in obtaining full APS thrust is not penetrated until  $R_{go} < 200$  ft.
5. Forward velocity is  $\leq 88$  ft/sec at  $R_{go} = 2000$  ft.

In considering steep glide-slope trajectories, (3) is violated, of course.

Another constraint of unknown documentation which has been used for past targeting of the visibility phase is

to keep the vertical rate of descent below a certain value at 500 ft altitude. This value has been 16 ft/sec for the Apollo 11-12 trajectories. For the steep trajectories considered in this study, this constraint completely dominates the others, i.e., if it is met, constraints 1, 2, 4 and 5 above are met. It is therefore used as a primary parameter for targeting the visibility portions of the trajectories in this study.

The trajectory followed from high gate to low gate is entirely dependent upon the high gate state (position and velocity with respect to the landing site) and the target constants (vertical and horizontal position, velocity, and acceleration and horizontal jerk) which are used by the explicit guidance steering routine for thrust direction and magnitude control of the LM. In the visibility phase targeting scheme used here, the altitude of high gate and its angle above the plane containing the landing site ( $\geq$  minimum elevation angle) are chosen as program inputs. This fixes the two position components at high gate. The position and velocity target components are also chosen to produce a low gate state which is acceptable for beginning the final landing phase. For this study, the vertical and horizontal components of position and velocity used were 80 ft, -20 ft, 0 ft/sec, and 0 ft/sec respectively for all trajectories. For targeting, the mass at high gate is assumed to be 19,000 lb. This value is modified after the braking phase of each trajectory is determined. The high gate velocity components are initialized in polar coordinates. The initial thrust of the visibility phase is fixed at 58% of the 10,500 lb maximum thrust. The high gate velocity magnitude is adjusted so that this initial thrust magnitude is correct. The angle between the velocity vector and the local horizontal is set so that the minimum elevation angle constraint is met. The jerk component (and initial time-to-go) is adjusted so the vertical rate constraint at 500 ft altitude is met. The target acceleration components are iteratively adjusted to minimize the  $\Delta V$  of the visibility phase.

#### B. Braking Phase

The braking phase is targeted using a program with the ignition altitude, speed, and mass and the high gate state being fixed inputs. The program chooses the ignition point up-range angle from the landing site and the vertical and horizontal acceleration and horizontal jerk target constants.

These four parameters are chosen to minimize the  $\Delta V$  to reach high gate and insure that the 120 second throttle-down time constraint following the full thrust period is met. The four position and velocity target constants are chosen so that the correct high gate state is reached. The high gate states used for braking phase targeting are those determined by the visibility phase targeting program.

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